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THE EFFICIENCY OF LOCOMOTION

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16. Abstract

Efficiency in walking was measured by using a tow rope, or a descending slope, to balance energy requirement until the minimum energy was attained at 4 kg pulling force. Walking work was 0.065 mkg per meter of distance and per kilogram of body weight. The efficiency was 26-27%. Maximum efficiency was reached at 2 - 3 kg opposing force, where efficiency was 31%

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THE EFFICIENCY OF LOCOMOTION

Erich Albert Müller

Let us define efficiency, as usual, as the ratio of the useful work produced externally to the energy used for this work. Then calculation of an efficiency for locomotion depends on knowing the external work produced in locomotion. Determination of this work has been undertaken often by different ways and with varied results. /236*

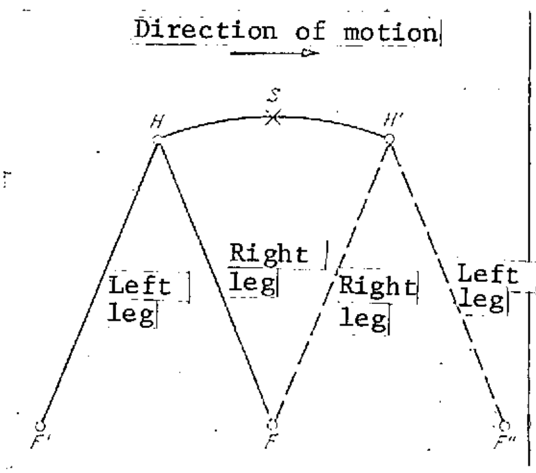

Figure 1

Some authors have attempted to calculate the external work of locomotion from the lifting work applied to the body's center of gravity at each step. They have realized that the raising and

* Numbers in the margin indicate pagination in the original foreign text.

lowering of the body's center of gravity in movement is an oscillatory process. If RL in Figure 1 is the extended right leg, which can be rotated in the foot joint, F, and in the hip joint, H, then the body mass, in its forward motion, is lifted along the arc HSH' to the apex, S, by means of its kinetic energy, which is partially converted to potential energy in the process. At a walking speed of 4.8 km/hr and a body weight of 60 kg, about 10 mkg of kinetic energy is available, while lifting the body by 5 cm requires only 3 mkg. The potential energy gained in the lifting is mostly reconverted back into kinetic energy of forward motion along the arc SH'. In the absence of friction, there must be exactly as much kinetic energy at point H' as at point H. / 237
(Of course, at a walking rate below 2.5 kg/hr the step length must be reduced so that the height difference between H and S cannot be overcome by the kinetic energy of the body mass.) The lifting of the body in locomotion cannot then, be considered as external work.

Atzler and Herbst [1] attempted to determine the external work of walking as follows: They determined the energy in unaffected walking and in pulling carts with a hand grip. The rolling resistance of the carts was dimensioned so that the

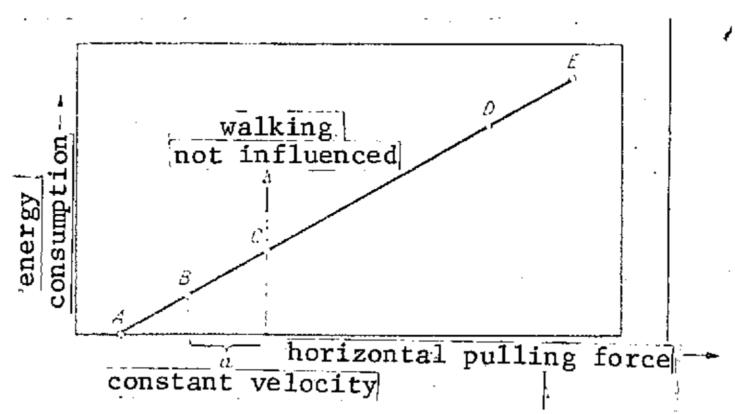

Figure 2

necessary force of horizontal pull was between 10 and 16 kg. The authors found that with a favorable step rate and step length the energy consumption for unaffected walking, C, and the energy consumption for pulling with forces of 10 and 16 kg (D and E, respectively) were on a straight line if the energy consumption is plotted on the ordinate and the horizontal pulling force on the abscissa (Figure 2). They assumed that the intersection, A, of the extension of this line with the abscissa represented the force to be overcome in the direction of motion for unaffected walking; i. e., the walking resistance. In this way they determined a walking resistance of 5.2 kg. This assumption rests on the erroneous assumption that the energy consumption becomes zero if the walking resistance becomes zero. This is not the case, however. Given a wind at one's back, just enough to overcome the walking resistance, there would still be a considerable energy expenditure for picking up, shorting, swinging forward, and setting down the legs, for balancing the body, and for the friction in the joints and tissues. This idling work of locomotion causes an energy expenditure indicated as B in Figure 2. Obviously, its value cannot be determined from the three points, C, D, E,, determined by Atzler and Herbst. Therefore, the walking work of 0.074 mkg/m reported by /238 these authors is too high, and the efficiency of 33% calculated from it is too high. The true walking resistance is shown in Figure 2 by the abscissa a of point B. Its determination would be physically possible with the method reported by W. O. Fenn [2] and von Rauhut [3], which records the horizontal forces between foot and ground in walking. Fenn found a resistance of 5 kg for running at 7.5 m/sec.

It is simpler to measure the walking resistance physiologically, though. If the body if freed of overcoming the walking resistance by a force acting horizontally in the direction of movement, then the energy consumption must be equal to B

(Figure 2). B, as the energy consumption of idling movement, is the smallest possible. The energy consumption minimum and the matching force which must correspond to the walking resistance can be determined by stepwise increase of the force acting on the walking person in the direction of movement. The walking speed and rate of stepping must be kept constant in this procedure.

It is possible to apply continuous measurable forces in the direction of motion to persons walking on a treadmill in three ways:

1. by a following wind;
2. through a pull in the direction of motion through a belt around the hips;
3. by going down a slope.

Both the latter two ways were applied in this study. Experiments on descending have already been done by Margaria [4]. He found the lowest energy consumption with a 10% slope for the treadmill. As he varied the slope only in steps of 5%, we cannot establish the walking resistance accurately from his results. Margaria himself did not calculate the walking work from this minimum. He stayed with the lifting of the body center of gravity in walking, a method which was criticized initially.

In our experiments, the test subject ran on a treadmill with constant speed and step rate. A pull in the direction of motion could be exerted with a weight applied through a cord passing over a ball-bearing-mounted roller with low moment of inertia to a wide belt around the hips of the test subject. A pull against the direction of movement (counter-pull) could be applied in the same way. A pull in the direction of movement was also produced by going down a tilted path. This pull is equal to the body weight times the sine of the angle of slope. The experiments were done on fasting test subjects in the morning.

The energy consumption was determined by the method of Douglas and Haldane during walking, ten minutes after the beginning of walking.

The two following test subjects were studied:

Table 1

Test Subject	Age years	Weight (clothed) kg)	Height cm	Bone Length cm 1	2	Basal Metabolism cal/min	Resting pulse	Walking speed m/min	Step rate per min
E. A. M.	47	60	173	44	48	939	60	80	120
E. U.	21	60.5	155	45	42	945	65	80	120

1 Thigh length

2 Lower leg length + foot height

Table 2 shows the average values of energy consumption for unaffected walking, for walking with a rope pulling in the direction of motion, and with counter-pull (opposite to the direction of motion) and for descending, for both test subjects. The mean errors of the averages are also shown. The variation is very small, especially for subject E. A. M. in the test series with a pulling rope, and only fluctuates about 1%. Figure 3 gives a survey of the result. The energy consumption decreases, from the point for unaffected walking, to a minimum with increasing pull in the direction of motion. This minimum appears at a pull between 3 and 4 kg for both test subjects. With the pull /240 increasing, we did not observe any sharp conversion to a renewed rise in energy consumption, as would probably have been expected on the basis of the increasing braking work which now must be provided. Rather, the energy consumption stays at the minimum

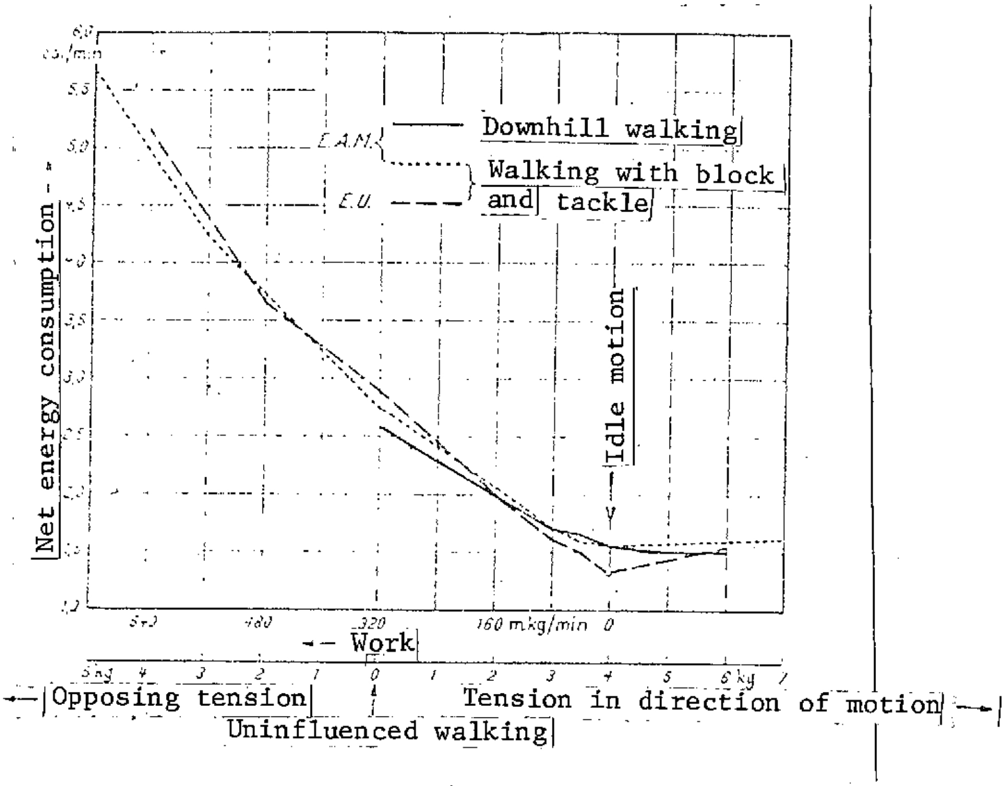

Figure 3

over a wide range and rises again only very gradually.

This curve shape can be explained in the following way: As long as the energy consumption is being reduced by increasing pull in the direction of motion, the walking resistance is certainly greater than the pull exerted. If the walking resistance is exceeded by the pull in the direction of motion, then an increase in energy consumption would immediately be expected because negative work (braking work) must now be exerted against the pull. But the body can statically compensate for the excess horizontal pull by simply leaning back. This requires very little energy and explains the slow rise in the energy consumption.

Table 2

Direction of Pull	Force of Pull kg	Slope %	Test Subject E. A. M. Walking with tow rope Cal/min	±[1] Cal	cal/m	Test Subject E. A. M. Descending Cal/min	±[1] Cal	cal/m	Test Subject E. U. Walking with tow rope Cal/min	±[1] Cal	Cal/m
Counter-pull	5		5749	17	72				—	—	—
	4		—	—	—				5161	0	65
	3		4247	41	53				—	—	—
	2		—	—	—				3635	36	45
Unaffected walking	0		2765	54	35	2566	95	32	2889	17	36
Pull in Direction of Movement	2.5		1912	37	24	—	—	—	1797	32	23
	3.0	5.00	1719	41	21	1708	104	22	1590	62	20
	3.5	5.85	1607	33	20	1661	20	21	1469	33	18
	4.0	6.67	1547	42	19	1517	74	19	1330	64	17
	5.0	8.33	1568	25	20	1505	84	19	1464	65	18
	6.0	10.00	1593	47	20	1486	52	19	1544	73	19
	7.0	—	1687	45	21	—	—	—	—	—	—

1 Mean error of the average

The energy consumption has a definite minimum only for test subject E. U. For E. A. M. one could be in doubt about the point at which the decrease in energy consumption ends. For descending in particular, the transition from decrease to constancy in energy consumption is very gradual. But between 2 and 3 kg pulling force, both curves show a drop of at least 0.3 cal/min. Between 3 and 4 kg, it is 0.15 cal/min. Between 4 and 5 kg pulling force, one curve rises again, while the other decreases by another 0.05 cal/min. One must be content, also with consideration of the order of magnitude of the mean error, in saying that the walking resistance is /241
about 4 kg. From this we calculate a walking work of 4 mkg/m of path, or 0.065 mkg/m per kilogram of body weight. In our experiments, the walking capacity was 320 mkg/min, i.e., 1/15 horsepower. This performance is achieved with an efficiency of 26-27%. If the walking resistance is eliminated by a pull of 4 kg in the direction of motion, and the walking work is therefore zero, then the remaining expenditure for movement corresponds to what has been called "idling motion" in the study of other work elements. This "idling motion" requires about half of the energy expenditure for walking. These data are summarized in Table 3 for our two test subjects.

The values in Table 4 were calculated from the averages for both test subjects in Table 2. The external work was inserted on the basis of the quantity of 4 mkg/m found for unaffected walking.

The values of Table 4 are presented in 2 curves in Figure 4. They show that the maximum efficiency is not attained in normal unaffected walking, but at an external work of 6 - 7 mkg; that is, with a counterforce of 2 - 3 kg, because the constant energy consumption of idling movement makes up an increasingly smaller proportion of the total energy consumption as the walking work increases. Climbing a 4 - 5% slope would about give the most favorable efficiency. A further increase in walking work / 242

Table 3

Test Subject	Walking Resistance kg	Rates		Net Energy Consumption cal/min		cal/mkg	Efficiency %	cal/m
		km/hr	mkg/min	unaffected walking	idling motion			
E. A. M.	4	4.8	320	2760	1550	8.6	27	34.5
E. U.	4	4.8	320	2800	1330	9.0	26	36.1

Table 4

Direction of Pull	Pulling Force kg	External Work mkg/m	cal/mkg	Efficiency %
Pull in the direction of movement	4.0	0		
	3.5	0.5	40.0	6
	3.0	1.0	21.4	11
	2.5	1.5	16.0	15
Unaffected walking	0	4	8.7	26.5
Counter-pull	2-3	6-7	7.6	31
	4-5	8-9	8.0	29.5

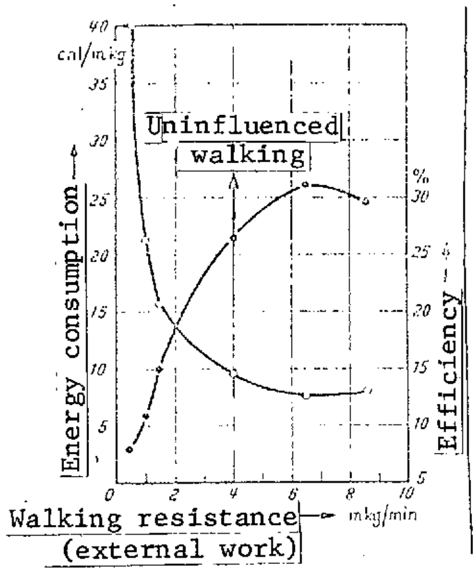

Figure 4

would reduce the efficiency again because the energy consumption does not increase linearly with the external work, but more rapidly (Figure 2).

With the methods we used, it would have been easy to decide whether the idling motion or the walking resistance is responsible for the rise of energy consumption with increasing walking speed observed by Atzler and Herbst. The relations in running can also be analyzed in the same way.

Summary

If increasingly larger pulling forces are allowed to act on the body during walking (pulling rope, descending slopes), the energy consumption decreases. It reaches a minimum at 4 kg. Therefore this force must be equal to the walking resistance, and the smallest energy consumption found must be the energy

consumption for idling motion. In treadmill experiments on two test subjects weighing 60 kg, for a walking velocity of 4.8 km/h, the idling motion required about half the energy expenditure for walking. Walking corresponded to a rate of some 5 mkg/sec or 1/15 horsepower. The walking work per meter of path and per kilogram of body weight was 0.065 mkg. It was provided with an efficiency of 26-27%. The highest efficiency (31%) was not attained in unaffected walking, but at 2-3 kg counter-pull or in climbing a 4-5% slope.

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